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Analysis of Inductance and Torque Characteristics for SR motor using Finite Element Analysis

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Abstract.
BACKGROUND/OBJECTIVES: SR(Switched Reluctance) motor has been attracted a lot of interest in research and development because of its low price, mechanically robust, high-speed rotation and high reliability due to its excellent characteristics at high temperatures.
METHODS/STATISTICAL ANALYSIS: Practical research and development for SR motors has advanced rapidly in the last 20 years because of the development of semiconductor devices and control technology. To practically reduce torque ripple and audible noise, phase current must be properly controlled, and for this, precise modeling techniques and analysis techniques must precede. In this study, the energy, inductance and torque characteristics of a motor were analyzed using finite element analysis.
FINDINGS: Magnetic field analysis and characteristic values of the motor were calculated through accurate finite element analysis considering the nonlinear characteristics of the magnetic body. It is useful to analyze dynamic characteristics as the excitation method changes by calculating energy, inductance and torque profile, which are important parameters of SR motor.
IMPROVEMENTS/APPLICATIONS: This study is a method that can respond quickly to determining the dimensions according to the change of the excitation method in the initial design stage of the motor.

Keywords: Inductance profile, Magnetic energy, Maxwell stress tensor, SR motor, Torque profile.

1. INTRODUCTION

In recent years, with the amazing development of the semiconductor industry, power conversion devices using semiconductor devices are widely used to drive electric motors. In particular, by using a switching semiconductor in the motor system, the characteristics of variable speed have been dramatically improved. Electric motors using these switching semiconductors were already recognized for their theoretical validity long ago. Electric motors that have not been realized due to economic or technical problems are being developed again for practical use. One of them is SR(Switched reluctance) motors, which has been actively developed and commercialized because its practicality is proven.

The term switched reluctance was first derived from a rudimentary disk-shaped switched DC motor with axial air gap developed by Nasar in 1969[1]. The principle of the first SR Motor was proposed by Davidson of the UK in 1838, but it has not been realized due to technical problems, but due to the development of semiconductor technology, a new study on SR Motor has been started[2]. In domestic, interest in SR Motor spread rapidly, centering on universities and research institutes. The application is being actively researched on the possibility of electrical appliances, industrial devices, and electric vehicles as traction motors.

SR motor is a structure in which only the stator has a winding and the rotor has a salient pole shape. In addition, the position of the rotor is detected using a sensor, and the corresponding stator winding is excited to obtain a driving force in the same direction. Since there is no excitation device in the rotor of the motor, there is no need for slip rings or brushes devices. For that reason, maintenance is also simple and there are few problems with temperature rise. In addition, since the generated torque is independent of the switching direction of the phase current, the driving circuit can be configured simply. Even if a short through fault occurs between windings, it does not affect other phases[3]. In addition, SR Motor is capable of ultra-high-speed operation and has the advantage of having constant torque characteristics over a wide range of speeds[4]. SR motor is expected to be widely adopted in home appliances and industries in the future, considering its operational efficiency and economics.

However, since the excitation method of SR motor is driven by pulse type voltage source, the ripple of torque is large. Methods of reducing torque ripple include a method of properly designing the shape of a magnetic part of a motor and a method of appropriately controlling a phase current. In order to reduce the torque ripple by properly designing the shape of the motor, this method has many difficulties in practice because it is necessary to know the characteristics of the magnetic circuit at all operating points that appear differently according to the pattern of the phase current[5]. For this reason, many researches mainly deal with the method of reducing the ripple of torque by controlling the phase current. And SR motor has a higher audible noise than other types of motors. The audible noise appears large when the phase current changes rapidly. Currently, the stator vibrates in the radial direction, and this vibration generates an audible noise. When the motor is small, it has only the noise of an internal combustion engine moving under a light load, but in the case of a large size, audible noise becomes a serious problem. In the end, to substantially reduce torque ripple and audible noise, phase current must be properly controlled, and for this, precise modeling techniques and analysis techniques must be preceded[6].

There are four things to keep in mind for accurate analysis of SR Motor as follows. First, since the driving method is a pulsed voltage source rather than a sinusoidal wave, the rotating field theory used in the existing AC motor cannot be applied. Therefore, the analysis method should start from the basic electromagnetic theory. Second, the characteristics of SR Motor are markedly different depending on the control method of the driving circuit. In particular, the pattern of the phase current appears differently depending on the leading angle and the conduction angle, and as a result, the pattern of the torque also shows a different aspect. Therefore, it is necessary to analyze the motor in consideration of the control method of the drive system[7]. Third is the high nonlinearity of the magnetic core. SR Motor is operated in saturated region to increase energy conversion efficiency. In particular, local magnetic saturation is more severe in the protruding parts of the rotor and stator near the airgap. Therefore, nonlinearity must be considered for precise analysis. Fourth, since the SR motor is mainly used for variable speed driving, an analysis technique that considers the variation of the load and speed is required to analyze the accurate characteristics.

In this paper, the inductance and torque of the SR motor are calculated to help understand the electromagnetic characteristics of the motor and design the shape. The electromagnetic field analysis of the motor using the finite element analysis was performed as a current source problem to understand the concept of basic characteristics and shape of a motor.

2. NUMERICAL THEORIES

2.1 ELECTROMAGNETIC FIELD ANALYSIS

Finite element analysis was performed by constructing the governing equation of the current source electromagnetic field of the SR motor and considering the nonlinear characteristics of the magnetic body. Maxwell's equations are made up of equations that can express all macroscopic electromagnetic phenomena. Considering the assumptions and boundary conditions appropriate to the problem given in these equations and applying it to the problem, the problem can be analyzed. Equations can be expressed in the form of differential and integral, and described using the form of differential is as follows.

$$\nabla \times \mathbf{H} = \mathbf{J_s} + \frac{\partial \mathbf{D}}{\partial t} \qquad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (2)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad (3)$$

In SR motor, displacement current can be ignored and eddy current is not generated. That is, the above equation is summarized for the magnetic quasi-static system, and the case where eddy current does not exist in the system is as follows.

$$\nabla \times \frac{1}{\mu}(\nabla \times \mathbf{A}) = \mathbf{J_s} \qquad (4)$$

The above equation is the electromagnetic governing equation for a system such as SR Motor, and if the above equation is solved by substituting the boundary condition, the desired result can be obtained. Modeling in two dimensions is possible under the assumption that the analysis model is long enough in the axial direction to be analyzed in two dimensions. In two-dimensional analysis, the magnetic vector potential and source current density are as follows.

$$\mathbf{A} = A(x, y, t)\,\widehat{a_z} \qquad (5)$$

$$\mathbf{J_s} = J_s(x, y, t)\,\widehat{a_z} \qquad (6)$$

Therefore, the vector partial differential equation (4) becomes as follows when interpreted in two dimensions.

$$\frac{1}{\mu}\frac{\partial^2 A}{\partial x^2} + \frac{1}{\mu}\frac{\partial^2 A}{\partial y^2} = -J_s \qquad (7)$$

2.2 ENERGY CALCULATION

In a static magnetic field, a magnetic pole or magnetic charge is assumed, and the static magnetic field is defined, and the energy relation in the magnetic field can be obtained similarly to the method of deriving the energy relation in the electrostatic field using the scalar magnetic potential. However, since it is not efficient to introduce a new quantity for the corrected magnetic field to derive only the energy relational equation for the magnetic field, I will only quote the resulting equation here. When the linear relationship between the magnetic flux density and the magnetic field intensity is established, the total energy accumulated in the normal magnetic field is as follows. Using the results of finite element analysis, the magnetic field energy in the entire motor range was calculated and presented for various parameters[8].

$$W_m = \frac{1}{2}\iint_s \mathbf{B} \cdot \mathbf{H}\; ds \qquad (8)$$

2.3 INDUCTANCE CALCULATION

To define inductance, it is necessary to first introduce the concept of flux linkage. Suppose that the current I flows through the toroidal coil with the number of turns , resulting in a total magnetic flux ϕ. First, suppose that this magnetic flux interlinks with each winding with N number of turns. At this time, each winding is linked with the magnetic flux ϕ. The flux linking $N\phi$ is defined as the product of the number of turns N and the flux linking each winding ϕ. The inductance was calculated using the relationship between the current and the flux linkage, and the inductance profile according to the change of the current was shown[9].

$$L_{ij} = \frac{\phi_{ij}}{i_i} \qquad (9)$$

2.4 TORQUE CALCULATION

Lorentz electromagnetic force density was introduced to calculate the torque generated in the rotor of the SR motor. This is expressed as follows by applying the Quasistatic approximation.

$$\mathbf{f} = \mathbf{J} \times \mathbf{B} = \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} \qquad (10)$$

The electromagnetic force received by volume V in the 3D analysis is as follows. Applying Gauss law to this equation is simplified as follows.

$$\mathbf{F} = \int \mathbf{f} \ dv = \frac{1}{\mu_0}\left[\int (\mathbf{B}\cdot\nabla)\mathbf{B} \ dv - \oint \frac{1}{2}B^2 \ \hat{\mathbf{n}}) \ ds\right] \qquad (11)$$

Here, s is the surface of the volume v, and $\mathbf{n}$ is the normal unit vector perpendicular to the surface s. Since the electromagnetic force acting on an object of volume v is equal to the area division of the Maxwell stress tensor acting on the surface s of the object, the electromagnetic force can be expressed using this as follows.

$$\mathbf{F} = \oint \mathbf{P} \ ds \qquad (12)$$

Since a two-dimensional analysis is performed in the electromagnetic field numerical analysis, the integral path is expressed as a straight line on the x-y plane. Also, the magnetic flux density within the element is constant. The following shows the Maxwell stress tensor used in numerical analysis[10,11].

$$\boldsymbol{P} = \frac{1}{\mu_0}(\hat{n}\cdot\mathbf{B})\ \mathbf{B} - \frac{1}{2\mu_0}B^2\,\hat{n} \qquad (13)$$

The electromagnetic force was modeled using the Maxwell stress tensor, and the torque was expressed with respect to the change in current.

$$\mathbf{F_m} = \sum_{e}^{elem} \Delta\mathbf{F_e} = \sum_{e}^{elem} \mathbf{P}\ \Delta L \qquad (14)$$

3. NUMERICAL RESULTS

3.1 ANALYSIS MODEL

In actual motor operation, the SR Motor detects the rotor position and is driven by a voltage source by a driving device. The current input to the stator winding changes over time by the external voltage source and the impedance of the circuit as the motor rotates. Therefore, for precise analysis, the magnetic field of the motor and the driving circuit must be considered at the same time and analyzed. The equation of the driving circuit to be combined with the governing equation of the electromagnetic system of SR motor was discretized. The motor to be analyzed is composed of 16 poles of stator and 12 poles of rotor. In addition, the accuracy of the solution was improved by analyzing only 1/4 of the domain considering the symmetry of the analysis domain. Table 1 shows the specific specifications of the motor to be analyzed.

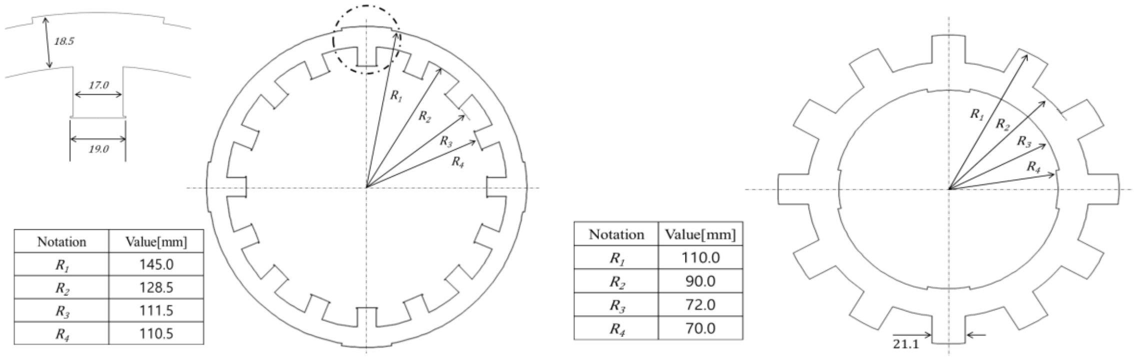
Table 1. Specification of the analyzed SR motors

Specification	Value	Specification	Value
Airgap	0.5 [mm]	Max. current	35 [mm]
No. of turns	150 [turns/pole]	Axial length	10 [A]
Rotor part		Stator part	
No. of poles	12	No. of phase	4
No. of slots	12	No. of slots	16
Arc of slot	11 º	Arc of slot	9 º

Diameter	220.1 [mm]	Diameter	290 [mm]
Width of slot	21.3 [mm]	Width of slot	19.3 [mm]
Depth of slot	20 [mm]	Depth of slot	16.5 [mm]
Thickness of yoke	20 [mm]	Thickness of yoke	17.0 [mm]

The data used in the static magnetic field finite element analysis process to calculate inductance and torque are the rate of change of the reluctance to the square of the magnetic flux density and the magnetoresistance to the square of the magnetic flux density. Therefore, it was calculated in advance from the magnetic characteristic curve.

Figure 1 shows the dimensions of the stator and rotor of the analysis model. The stator slot is 16 and the pole rotor pole is 12. The driving circuit of the motor used in the simulation uses a four-phase converter and is driven by a single-phase excitation method by the switching sequence. Figure 2 shows the winding arrangement of the motor stator. The Prime symbol indicates that the direction of the current is opposite.



a) Stator part **b) Rotor part**

Figure 1. Dimension of the analyzed SR motor

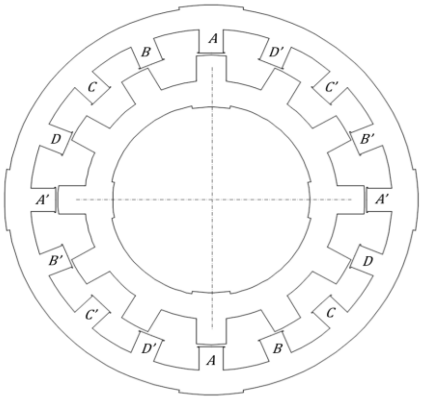


Figure 2. Winding distribution of the analyzed SR motors

The magnetic material needs a finite element nonlinear analysis because magnetic saturation occurs in which the magnetic flux no longer increases in the iron core as the current increases. In this analysis, iron core S60 was used for the stator and rotor cores, and the characteristic curve of the material is shown in Figure 3.

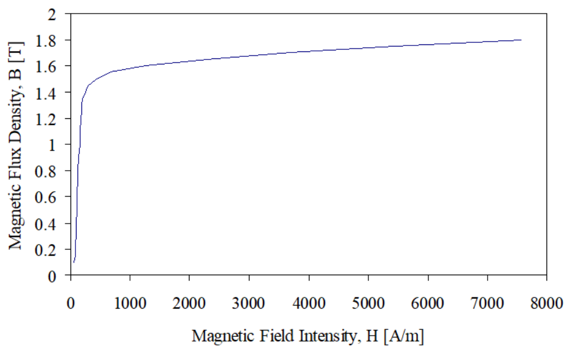


Figure 3. Magnetic characteristic curve

3.2 CHARACTERISTICS OF THE SR MOTOR

In this analysis model, the stator winding is four phases, and the number of slots of the stator and rotor is a multiple of 4. Therefore, not only the geometrical shape but also the magnetic properties form a 4 symmetrical structure, so it is possible to understand the magnetic distribution of the motor by analyzing only a quarter of the total area. Figure 4 shows the finite element mesh used in finite element analysis. Since the air gap of the motor has a complex shape and high energy density, the elements are intensively subdivided. In this analysis, 3,020 nodes and 5,230 elements were used to improve the analysis accuracy. Figure 5 shows the eq-potential line as the analysis result when the rotor position is rotated 10 degrees. The direction and magnitude of the torque is determined by how the magnetic flux paths of the stator and rotor are formed.

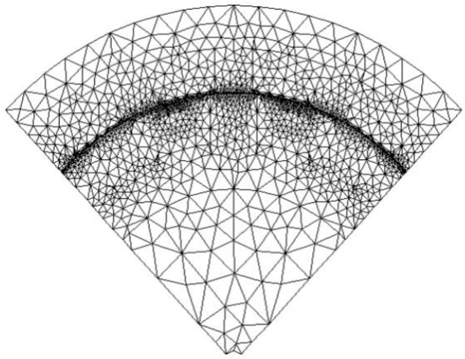


Figure 4. Mesh with 3,020 nodes and 5,230 elements

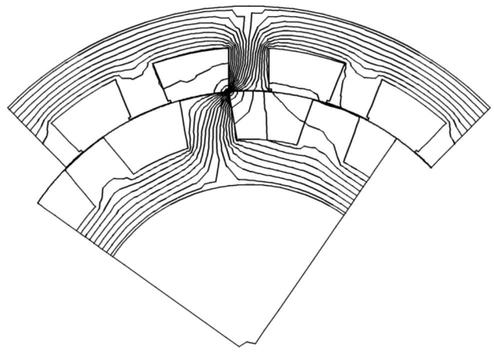


Figure 5. Equi-potential lines with 10[Deg.]

Magnetic energy refers to the potential that can be converted into mechanical energy in electric devices such as solenoid actuators and electromagnets. Electromechanical energy conversion is a conversion of mechanical energy into electrical energy(generator) or vice-versa(motor) with the aid of rotary motion(rotary machines) or translatory(linear) motion(actuators and linear machines). In lumped constant analysis, magnetic energy is expressed as the product of inductance and the square of the current divided by 2. In this study, the magnetic flux density and the magnetic field intensity were calculated by integrating the area using the results of finite element analysis. For both methods, the results are consistent, and it is assumed that this result will be similar to the inductance profile. Figure 6 shows the magnetic energy according to several currents and the position of the rotor.

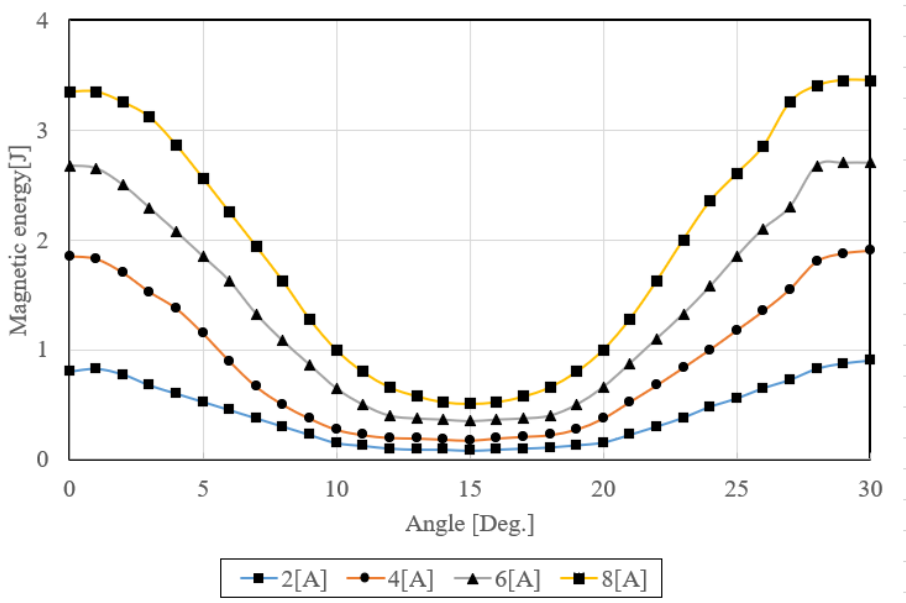


Figure 6. Magnetic energy according to rotor position

The input current entering the forcing term of the motor's governing equation is the amount that is input through the stator winding. The current changes over time due to various factors as the rotor rotates. Also, the value of this input current is determined by the impedance of the external voltage source and circuit. Therefore, the external voltage source circuit must be considered and analyzed at the same time. When analyzing the stator voltage equation of a motor, the term corresponding to the derivative of the flux linkage is expressed as the product of current and inductance matrix. Therefore, the inductance appears differently depending on the amount of current and the position of the motor. If the inductance profile is precisely calculated according to the current and time through finite element analysis, the accurate time difference analysis of the motor can be performed very quickly. Figure 7 shows the inductance profile according to the change of current and the position of the rotor. When the stator teeth and the salient pole of the rotor are aligned, the reluctance is small, so a large amount of magnetic flux is generated, and the inductance is large. On the other hand, if the stator and rotor poles do not coincide, the inductance is calculated small by the large reluctance. At points without data, inductance can be calculated by interpolating surrounding values.

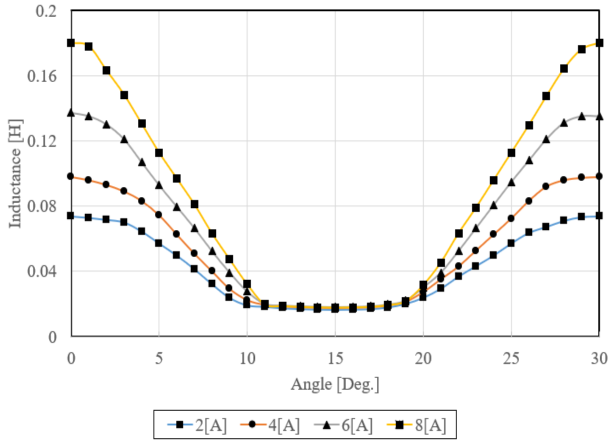


Figure 7. Inductance according to rotor position

In an electric motor, torque is a direct cause that enables rotational motion, and is a physical quantity closely related to output power. When analyzing the dynamic characteristics of a motor, accurate torque data are required. Figure 8 is the result of calculating the torque while rotating the rotor from 0 to 30 degrees and changing the current. Torque was calculated using Maxwell stress tensor. Since the drive coil is fixed and rotated, the result of origin symmetry is shown based on a specific position. When the current increases and when the stator teeth and the rotor poles are misaligned, the torque becomes large.

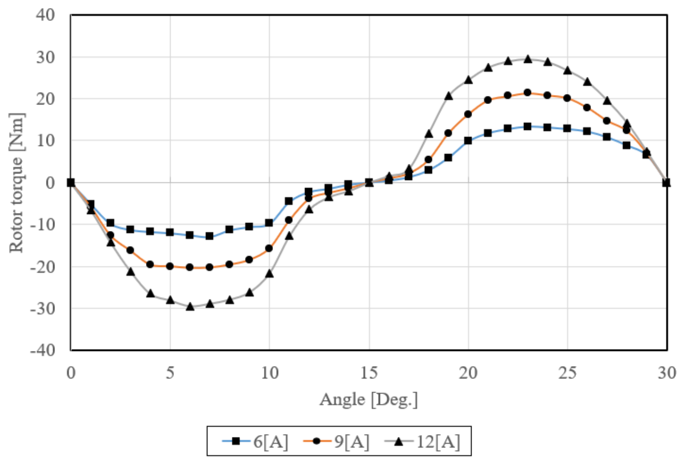


Figure 8. Generated torque according to rotor position

4. CONCLUSION

Magnetic energy, inductance and torque of SR motor were calculated through precise finite element analysis. The magnetic energy and inductance profile are effectively used for time difference analysis using parameters. This is used as a major parameter when solving the differential equation of a motor driven by a voltage source. The torque profile is an important factor in determining the output power of a motor when used as an important data for analyzing the dynamic characteristics of a motor. If a lookup table is used for the current and position of the main parameters of the motor, the results can be obtained more quickly than the time difference finite element analysis in the initial design and analysis of the motor.

5. ACKNOWLEDGMENT

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